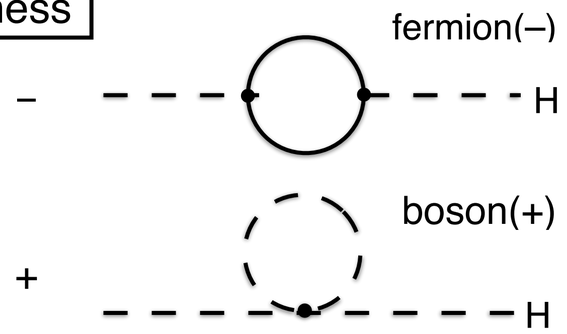
SUSY DM at the LHC

Indara Suarez, Sicheng Wang, Daniel Spitzbart

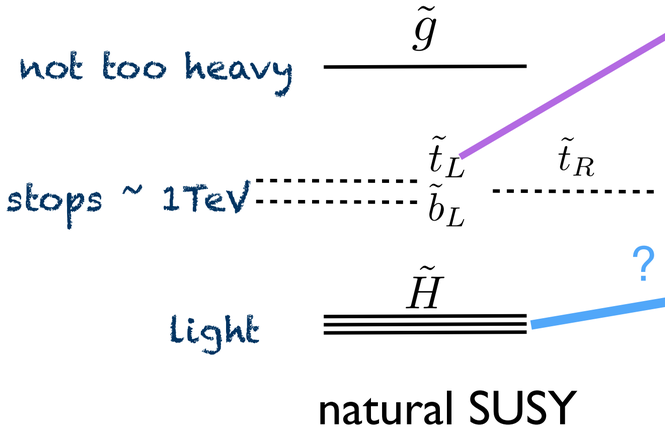
Why Supersymmetry

- An natural extension to the Standard Model
  - A lot of new particles to discover 😍
    - play an important role in canceling large corrections to Higgs mass in a *natural* way
    - decay into Lightest Supersymmetric Particle (LSP) —> Dark Matter particle candidate
      - Assuming **R-parity is conserved**
  - Particles within reach of the LHC
    - Relic density suggest WIMP ~ Electroweak scale

Naturalness

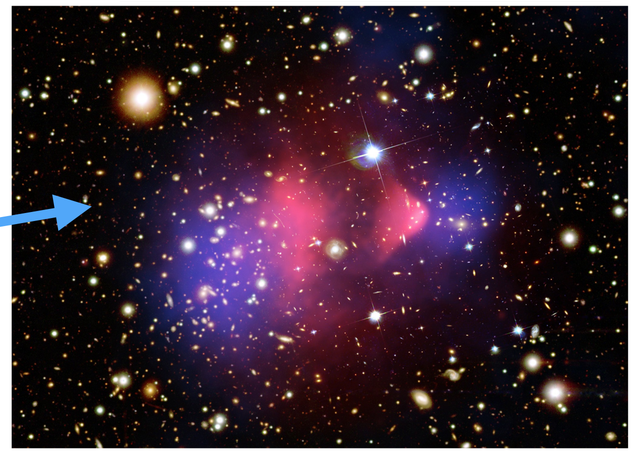


$$\delta m_H^2 \sim |y_t|^2 \left[-\Lambda_{\rm UV}^2 + \frac{3}{2} m_t^2 \log\left(\frac{\Lambda_{\rm UV}^2}{m_t^2}\right) + \Lambda_{\rm UV}^2 - m_{\tilde{t}}^2 \log\left(\frac{\Lambda_{\rm UV}^2}{m_{\tilde{t}}^2}\right) + \cdots \right]$$



Papucci/Ruderman/Weiler, arxiv:1110.6926

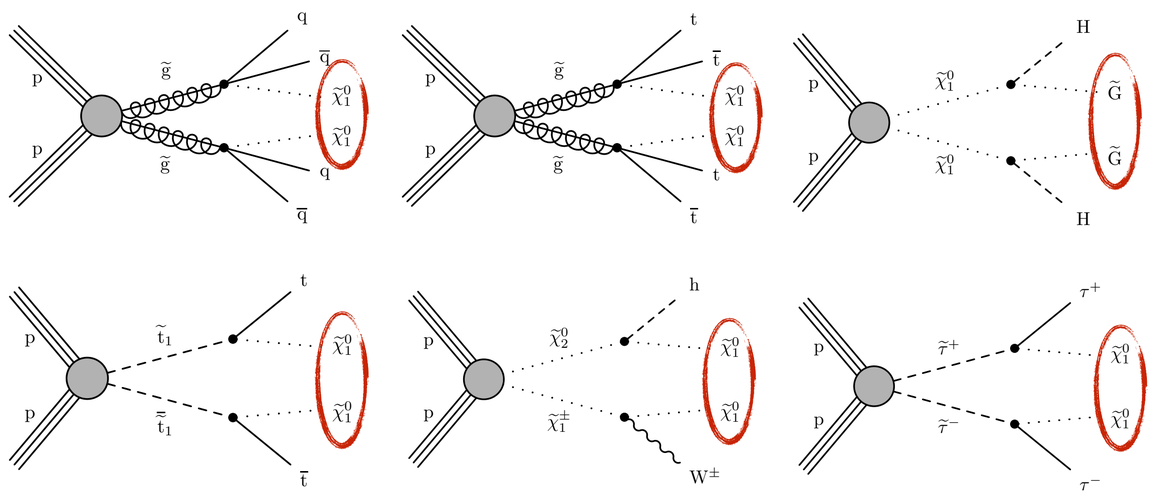
Abundant observational evidence for DM

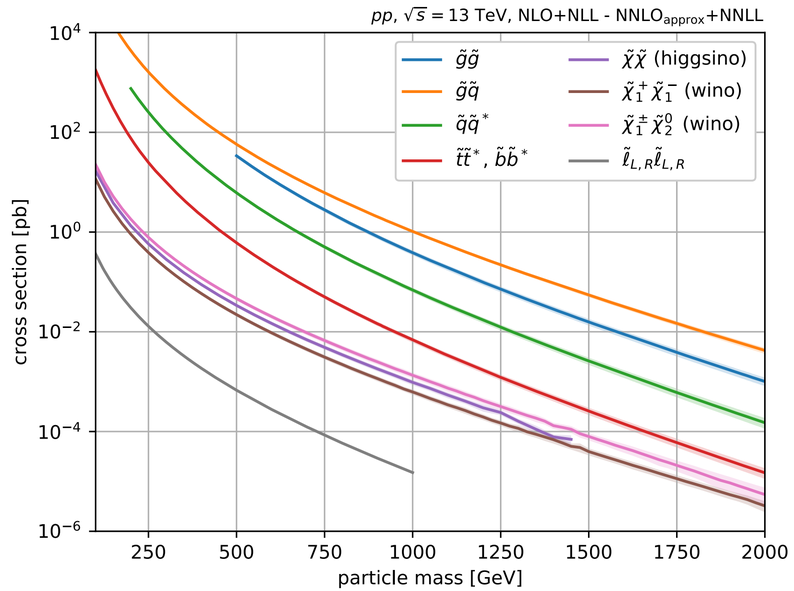


SUSY DM @ the LHC

- Comprehensive searches in CMS and ATLAS looking at a variety of production mechanisms for the DM candidate
  - Generic searches using experimental signature (e.g. #lepton, #jets)
  - Targeting the production of SUSY particles according to **simplified models**

Only looking at a few examples today!

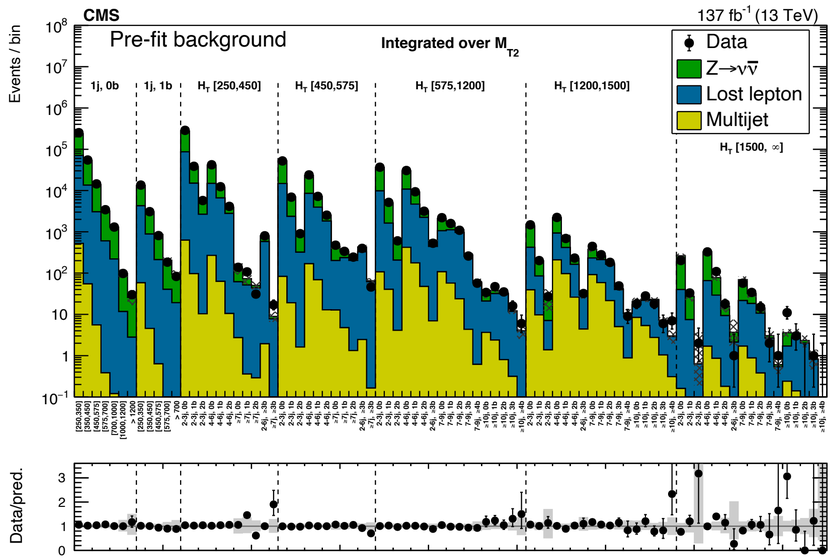


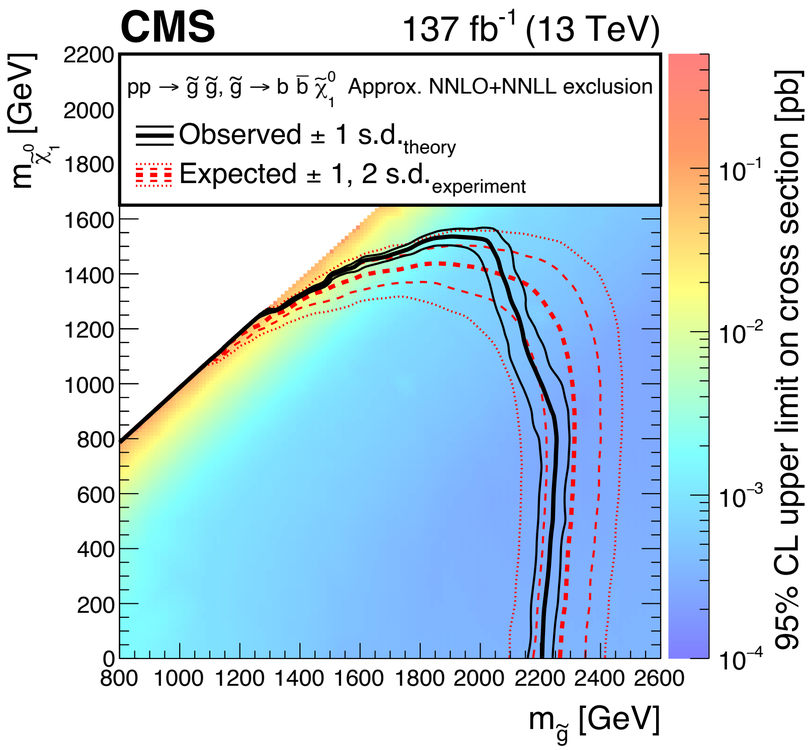


- Core strategy: Large missing energy from the DM candidate (LSP)
- **Rich phenomenology that allows us to probe the how DM can show up in collider experiments**
- DM limits are tied to their SUSY decay chains

Generic All Hadronic Searches

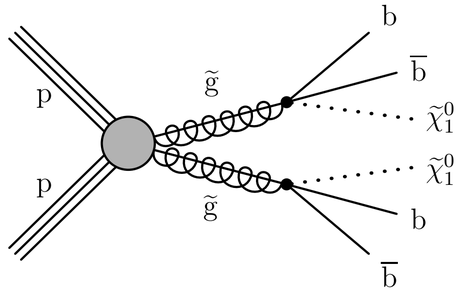
- Search in all hadronic final state
  - Probe the strong sector of SUSY
  - Gluino mass also constraint by naturalness
- Key strategy: constraint multi-jet with M_{T2}
  - Multi-binned cut-and-count
  - Background estimates all come from data
- Neutralino DM excluded up to 1.5 TeV





Eur. Phys. J. C 80 (2020) 3
[CMS-SUS-2019-005]

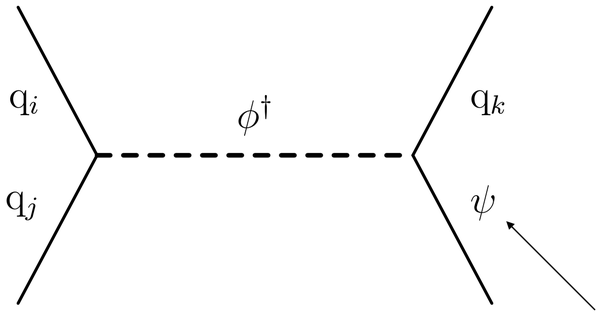
Complementary ATLAS result:
JHEP 10 (2020) 062



Versatility of All Hadronic Search

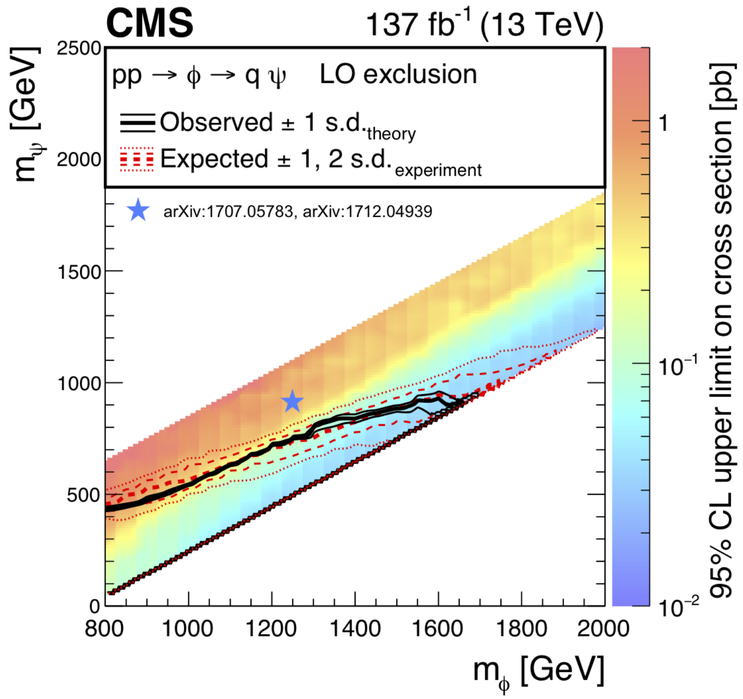
- Aggregated regions used in reinterpretation
  - Search consist of hundreds of mutual exclusive regions
  - Combining these search regions can go beyond simplified models
  - An ~3σ excess was found at previous iteration by external reinterpreter [arXiv:1707.05783]
  - Many non-SUSY interpretation is included in the run2 result

- Other interpretation with LQ also included
  - LQ reinterpretation can also be found at the recent ATLAS 0ℓ search: arXiv:2004.14060



P. Asadi, et al.
arXiv:1712.04939

Massive invisible fermion

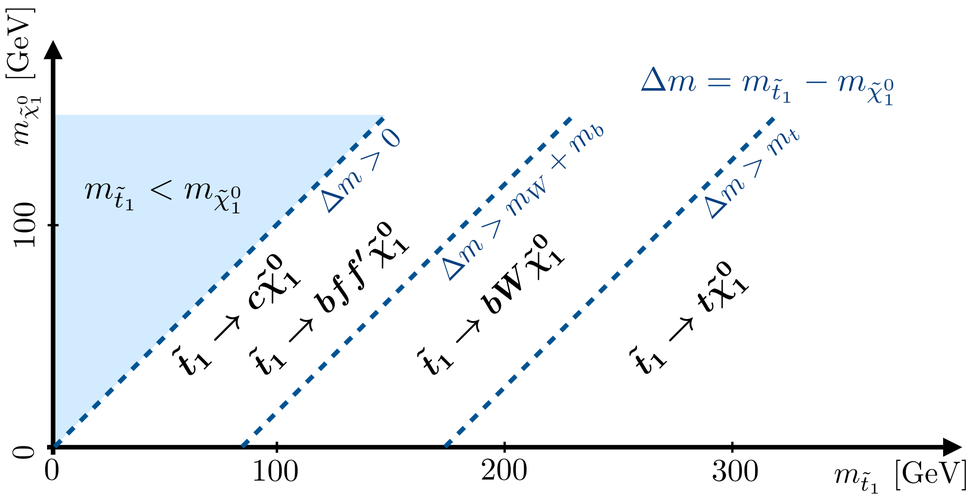


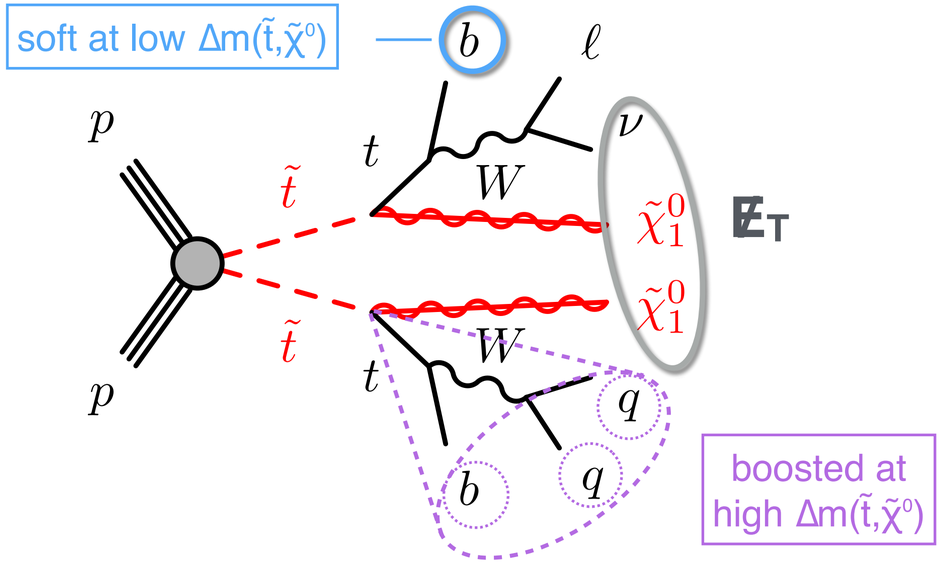
Eur. Phys. J. C 80 (2020) 3
[CMS-SUS-2019-005]

Searches for Stop + LSP

- Central piece to the naturalness problem
  - Lightest squark in natural SUSY scenarios
  - Searches with signature: $t\bar{t} + \not{E}_T$

- More difficult to probe in compressed spectra (low $\Delta m(\tilde{t},\tilde{\chi}^0)$ regions)
  - Using more stats to explore low $\Delta m(\tilde{t},\tilde{\chi}^0)$
    - Softer in object kinematics and $\not{E}_T$
    - New techniques on object tagging [recent]





Run2 results targeting at stop pair production:

0ℓ: arXiv:2004.14060 (ATLAS)

0ℓ: arXiv:2103.01290 (CMS)

1ℓ: arXiv:2012.03799v1 (ATLAS)

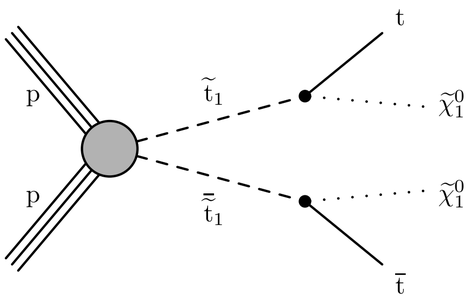
1ℓ: JHEP 05 (2020) 032 (CMS)

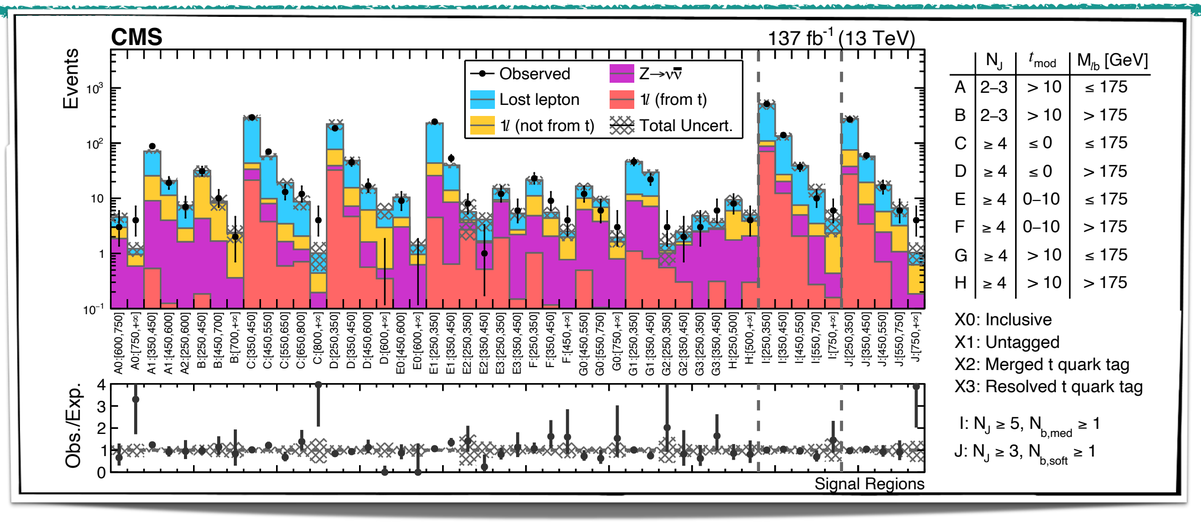
2ℓ: Eur. Phys. J. C 81 (2021) 3 (CMS)

CMS Combination: CMS-PAS-SUS-20-002

Search for Stop in 1ℓ

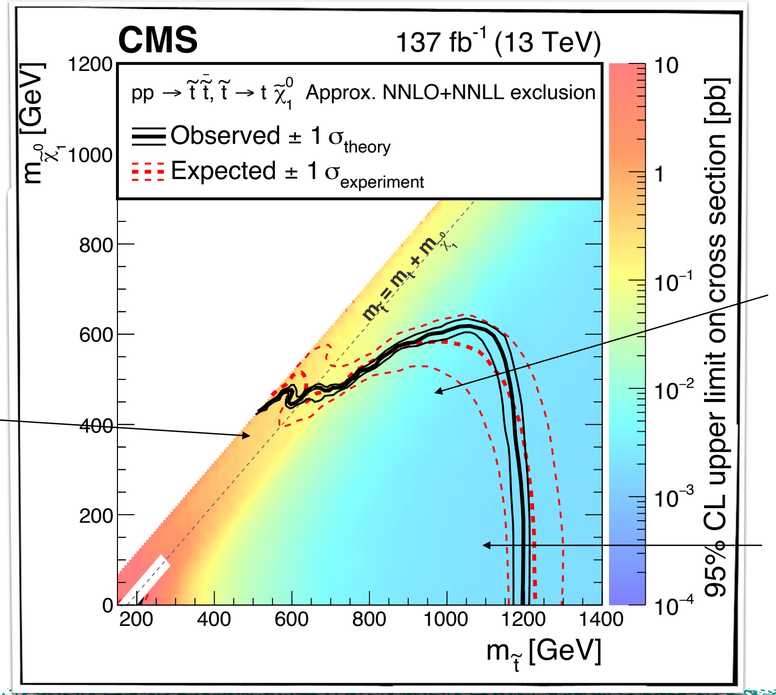
- Cut-and-count & multi-binned analysis
  - 39 search regions to cover variety of phase space and decay modes
  - Retaining ability for re-interpretations





	N_J	t_{mod}	M_{lb} [GeV]
A	2–3	> 10	≤ 175
B	2–3	> 10	> 175
C	≥ 4	≤ 0	≤ 175
D	≥ 4	≤ 0	> 175
E	≥ 4	0–10	≤ 175
F	≥ 4	0–10	> 175
G	≥ 4	> 10	≤ 175
H	≥ 4	> 10	> 175

JHEP 05 (2020) 032
[CMS-SUS-19-009]



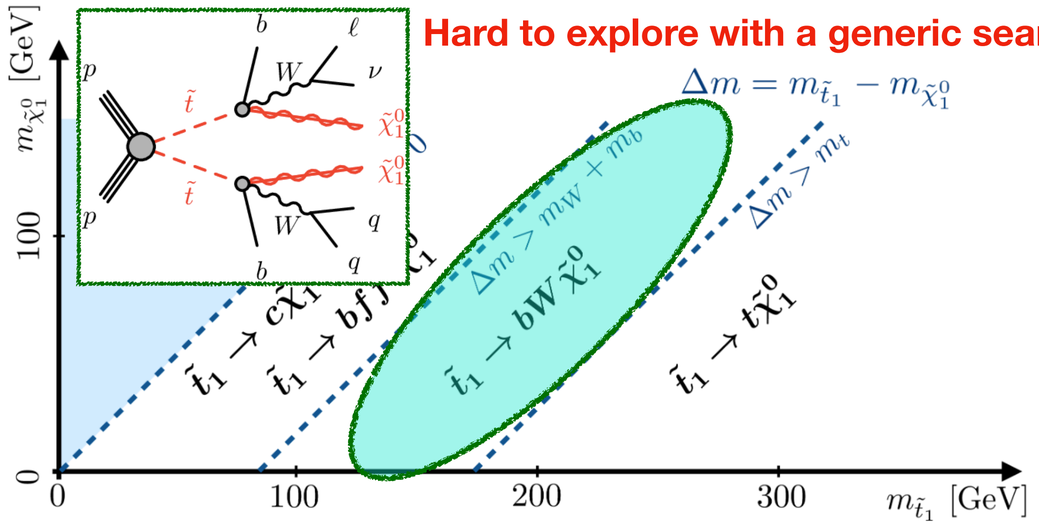
top-tagger (resolved)

soft-b

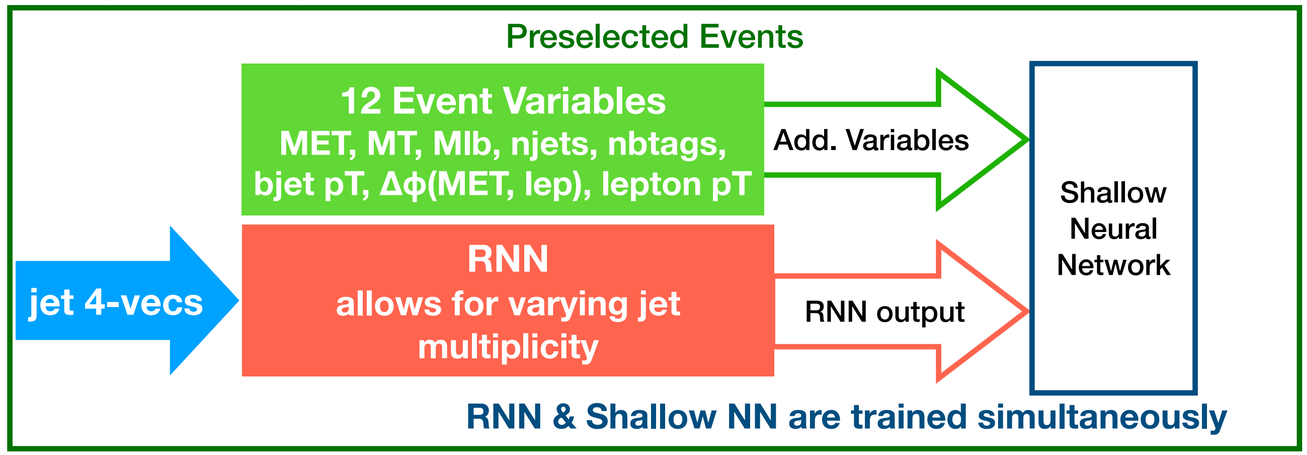
top-tagger (merged)

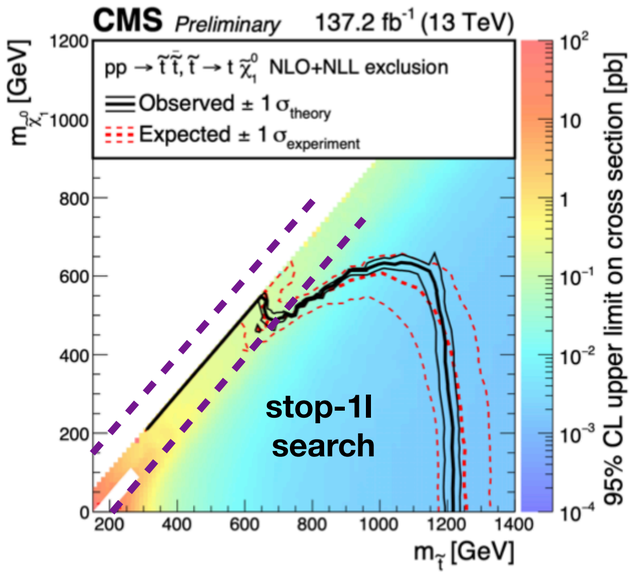
- Optimize with heavy object identification
  - Top-tagging for large Δm
  - Soft-b tagging for $\Delta m \sim m_W$

Search for Stop in 1ℓ

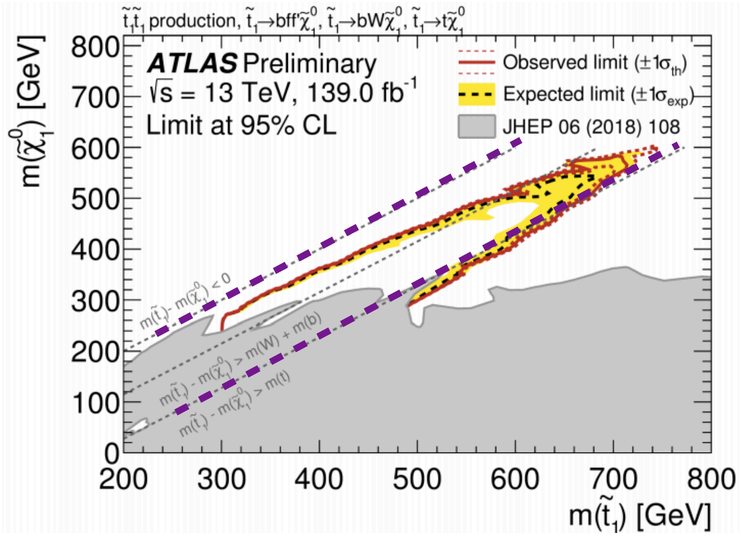


- Full Run-2 dataset also allows us to look into background heavy regions using new machine learning tools



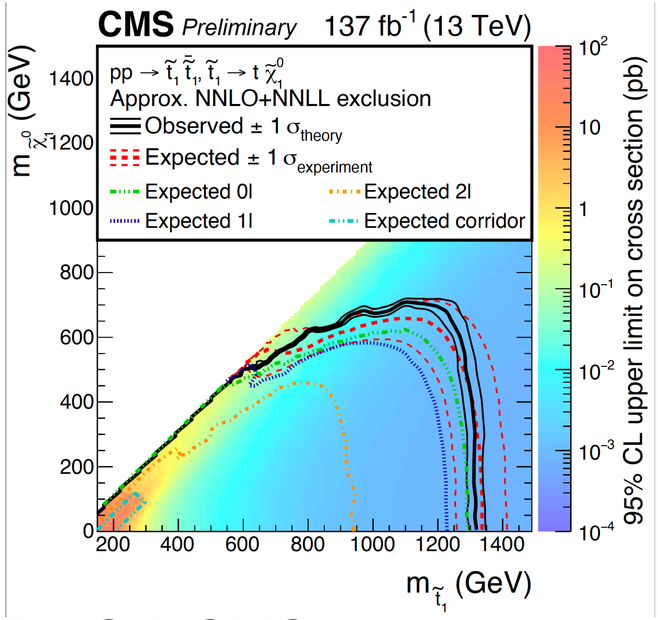


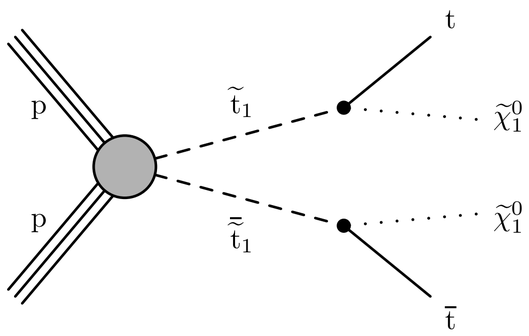
- Using soft-b ID
- exclusion up to ~ 600 GeV in stop mass

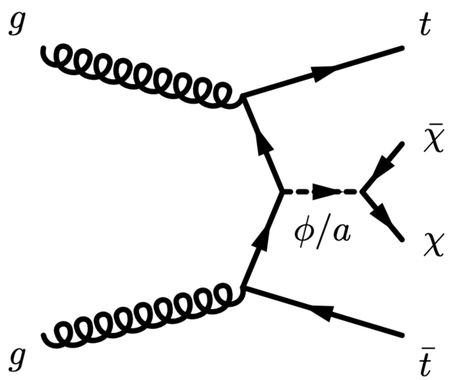


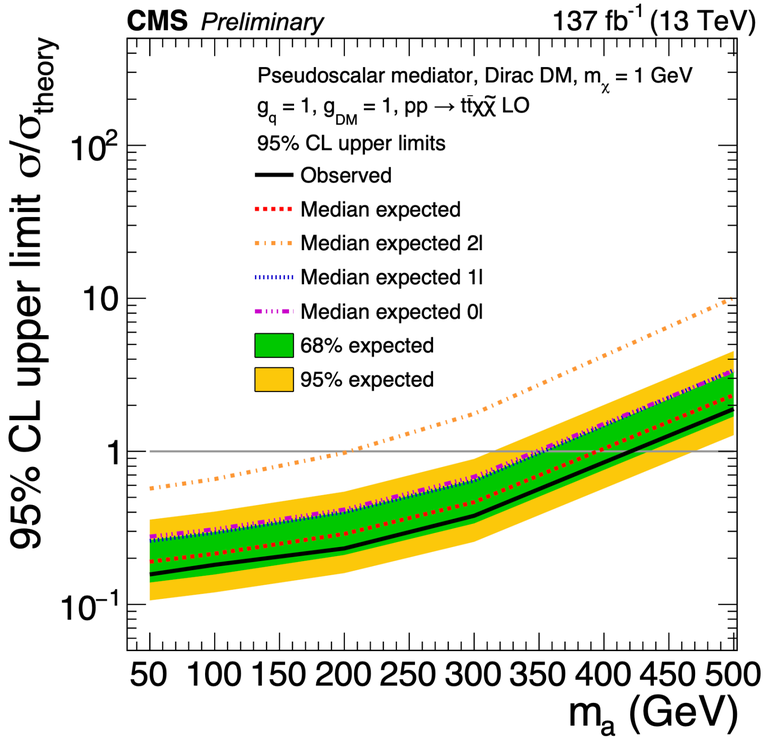
- Using ML: large improvement from previous limits: exclusion up to ~700 GeV in stop mass

Final states not unique to SUSY scenarios





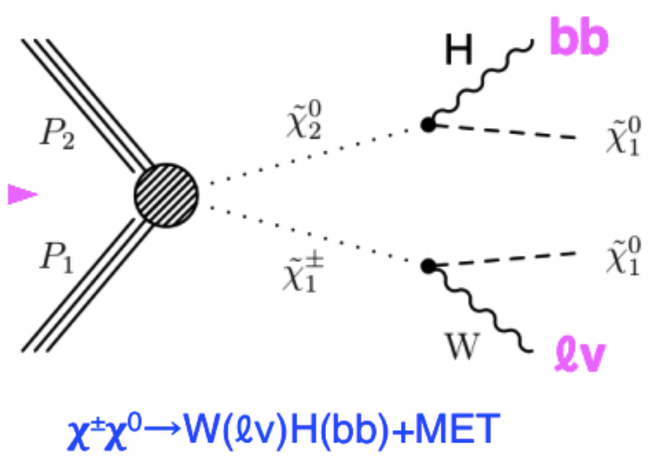




- ATLAS & CMS have interpreted their results in the $t\bar{t}$+DM model
  - Important channel for models with coupling to SM ~ y_t
  - First set of results that includes all Run 2 data and all top squark searches in CMS
    - CMS-PAS-SUS-20-002
    - Excludes mediator particle masses of up to 420GeV are set

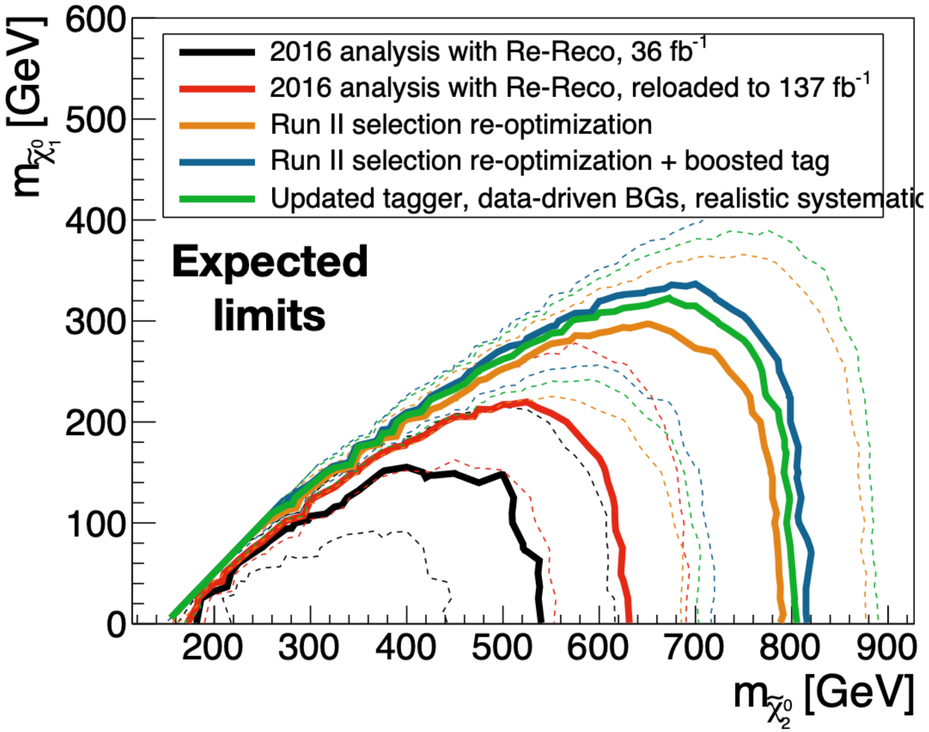
Searches for Electroweakino

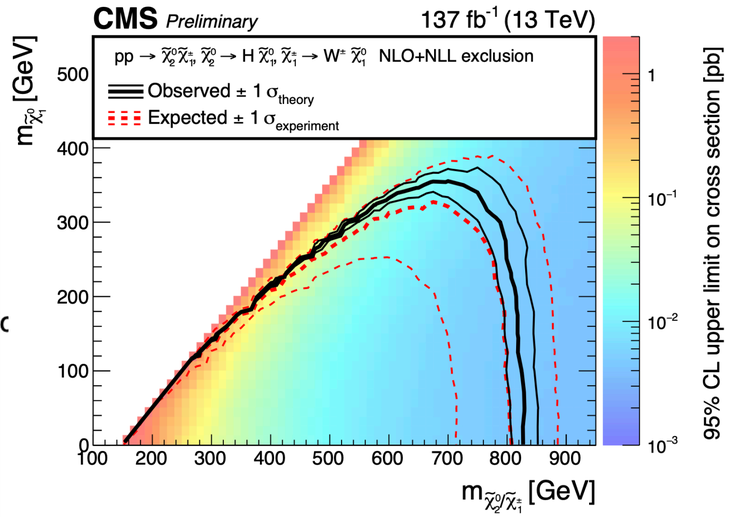
- Electroweakinos pair production
  - What if the strong sector is too heavy
  - With full Run 2 statistics can probe electroweakino sector



CMS-PAS-SUS-20-003

Perfect for use of new technology:
DNN heavy object taggers



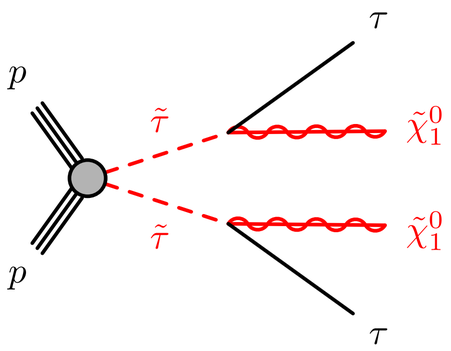


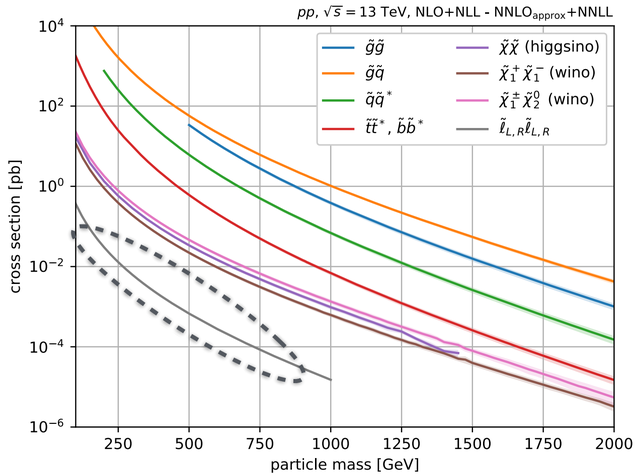
Searches for Staus

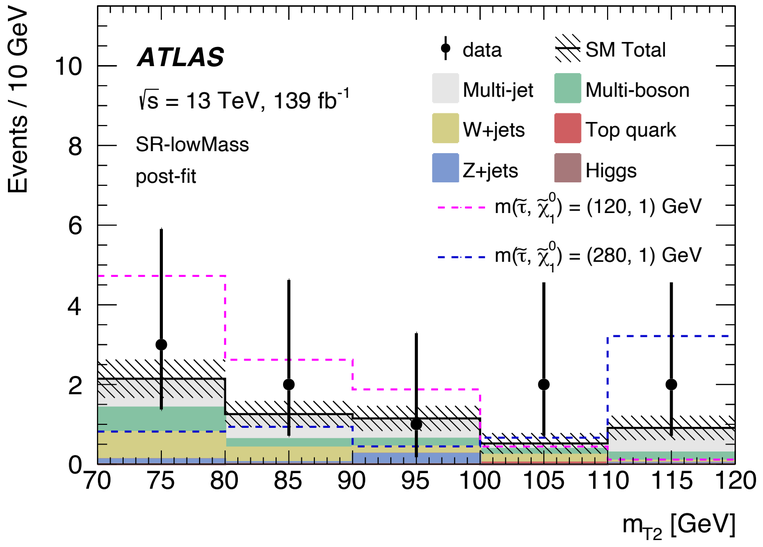
- Stau is also important in the SUSY model
  - Help in obtaining relic DM density

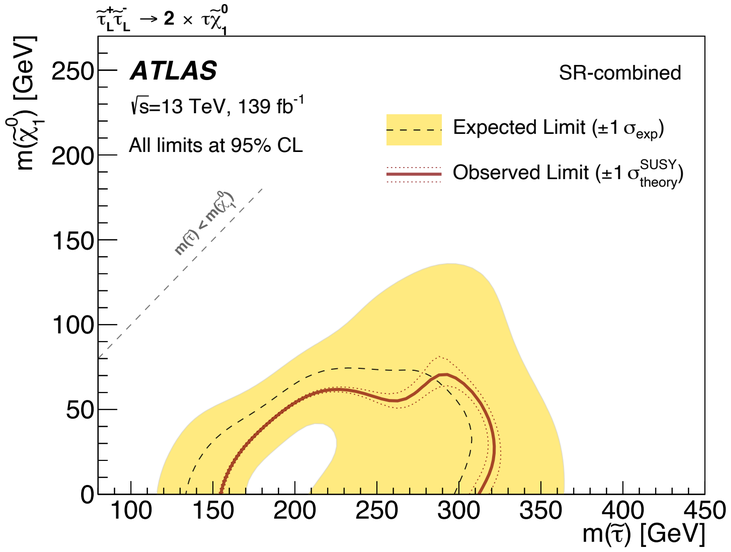
Phys. Rev. D 101, 032009 (2020)

- Challenging search
  - Most sensitive at $\tau_h\tau_h$ channel ⟵ misID
  - Search in moderate $\not{E}_T$ region
  - Search still limit by amount of statistics









Summary

- A variety of searches for the supersymmetry is performed at LHC
  - Low scale SUSY has been studied in depth
  - So far no consistent excess that can hint SUSY mediated DM production at LHC has been observed
    - Few more run2 results still coming out
- We have largely excluded the most prevailing notions of Dark Matter and naturalness at the collider
- Question for the next steps
  - How can more data help efficiently?
    - Can we revisit some of the more challenging area with our new tools?
  - Can the SUSY be hiding at space we overlooked?
  - Can we still have light neutralino DM?
  - More exotic signatures?

Going after some of the uncovered and more challenging areas with a new set of tools to identify tops, b's and taus.

New detector technologies

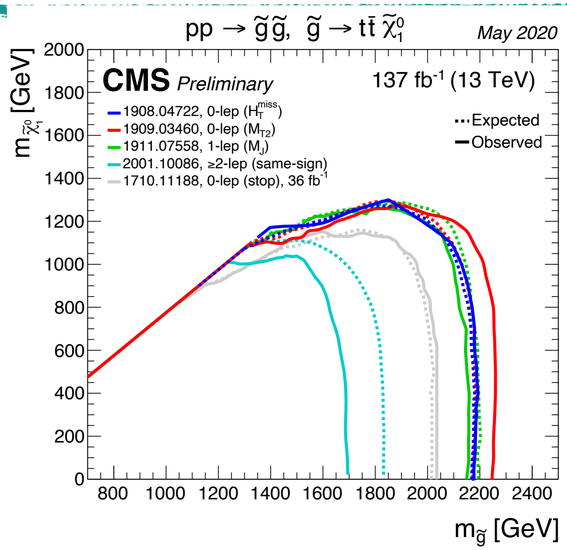
Summary plots from ATLAS
Summary plots from CMS

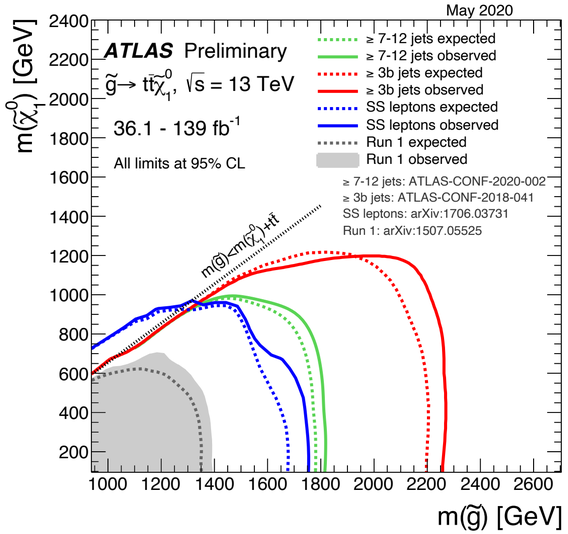
Diversity Through Research Mentorship

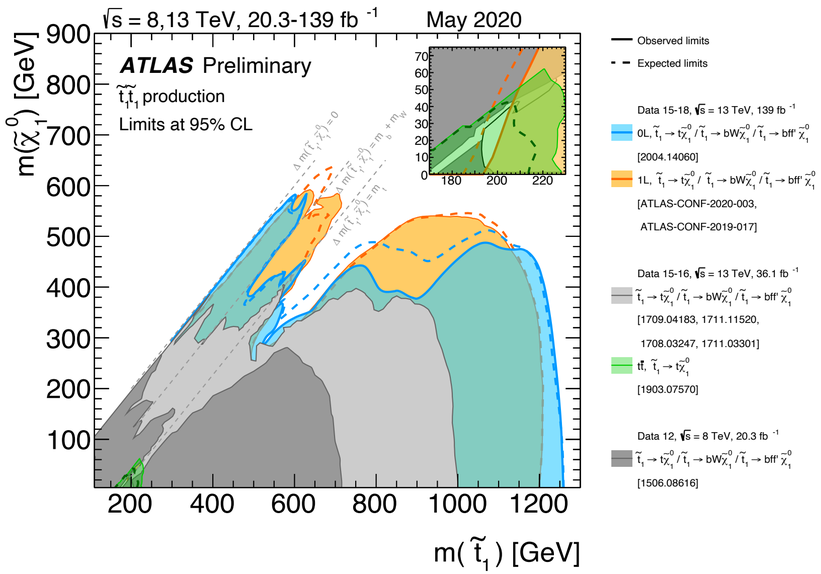
- My research group has many undergraduates
  - Recruit students during their freshman year to learn skills related to research in particle physics → create a community
  - Involve them in projects where they can make unique contributions → help them establish their physics identity and prepare them for various careers (academia & industry)
  - Bridge them into other programs (REUs, internships, graduate programs) → invest in their future
- Students are paid for research work through University Funding, work study, or grant funding
- Idea based on the TEAM-UP report, conversations with Flip Tanedo, Frank Golf, and Daniel Spitzbart

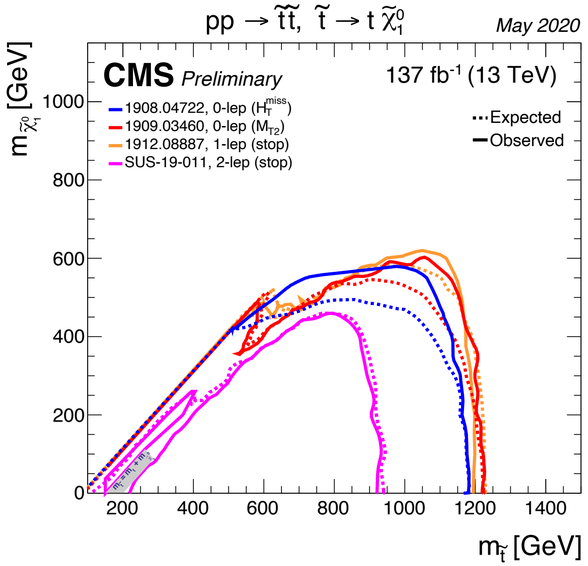
Backup

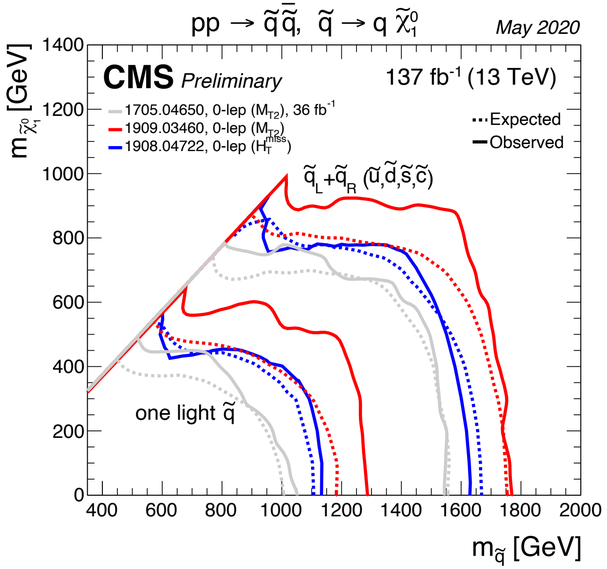
Other Summaries

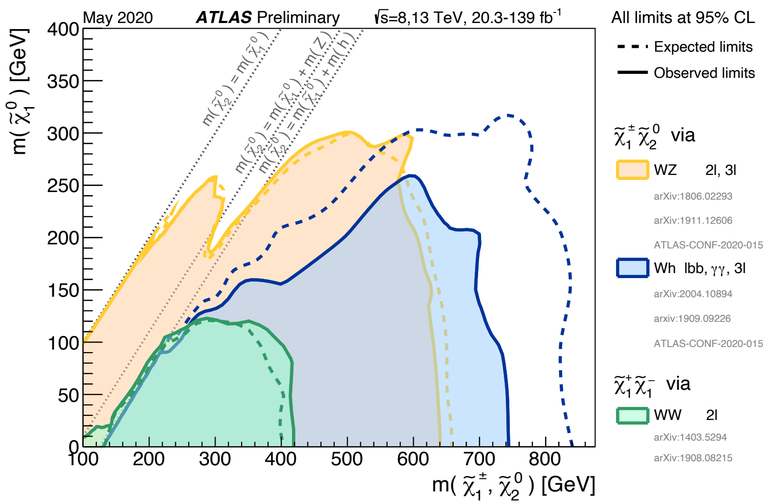








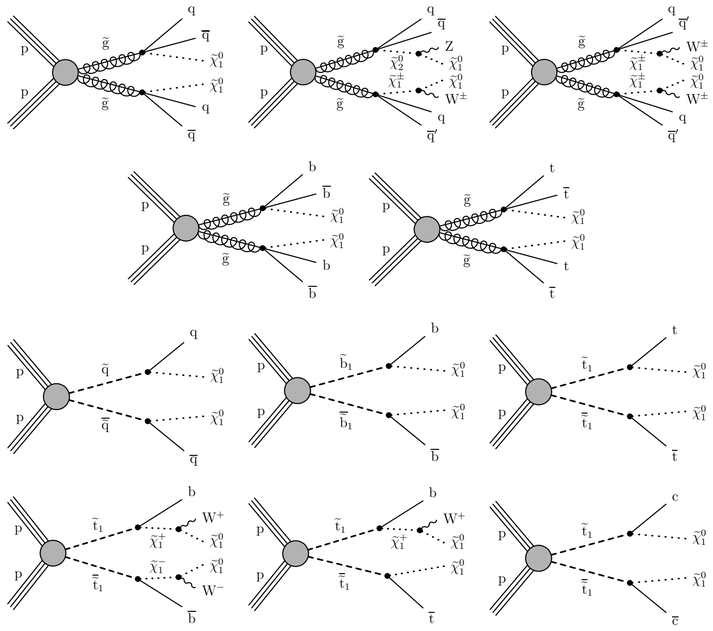


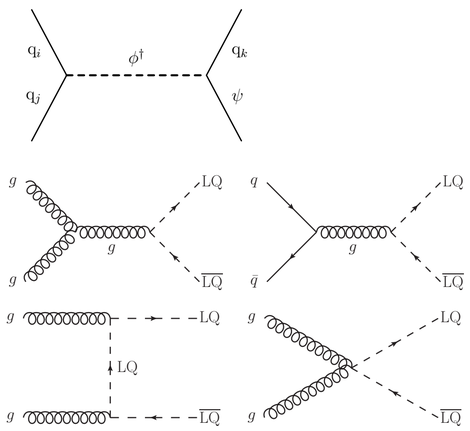


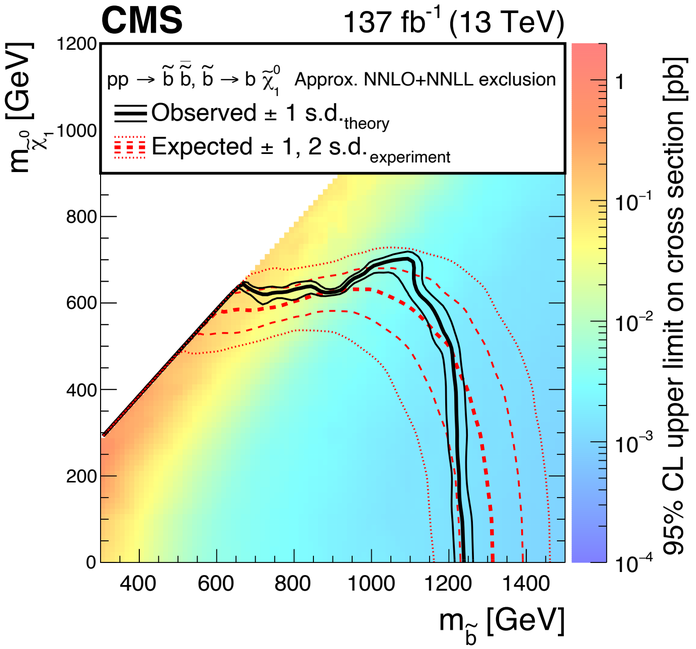
CMS All Hadronic Search

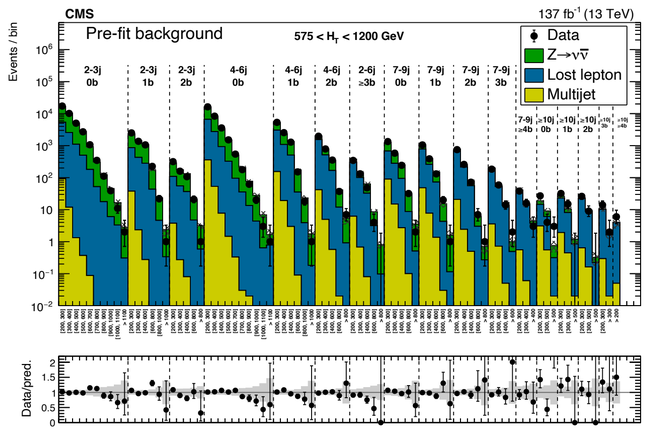
- Background estimated from data driven methods
  - Irreducible $Z(\nu\bar{\nu})$ from $Z(\ell\ell)$
  - $t\bar{t}$ (lost lepton) from $t\bar{t}\rightarrow 1\ell$
  - Left-over QCD from jet rebalance & smear

$$M_{T2} = \min_{\vec{p}_T^{\,miss\,X(1)} + \vec{p}_T^{\,miss\,X(2)} = \vec{p}_T^{\,miss}} \left[\max\left(M_T^{(1)}, M_T^{(2)} \right) \right]$$



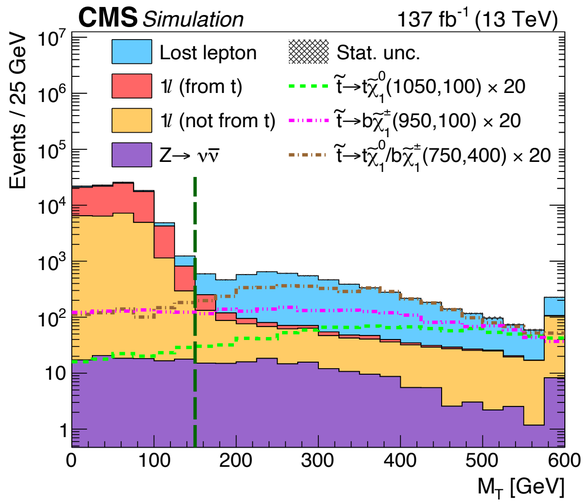


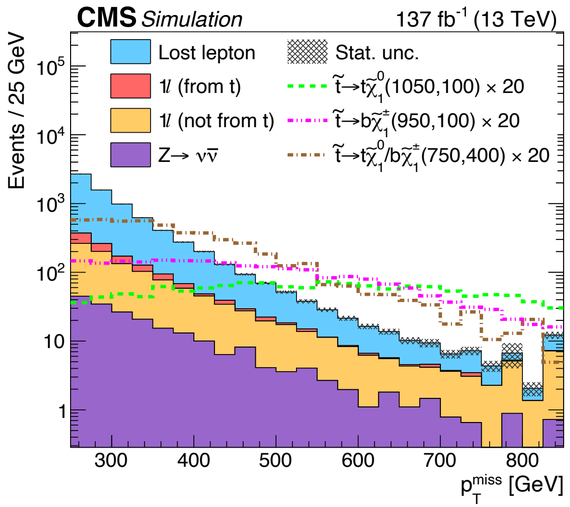




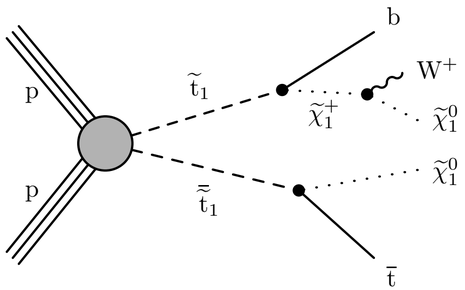
CMS Stop-1ℓ Search

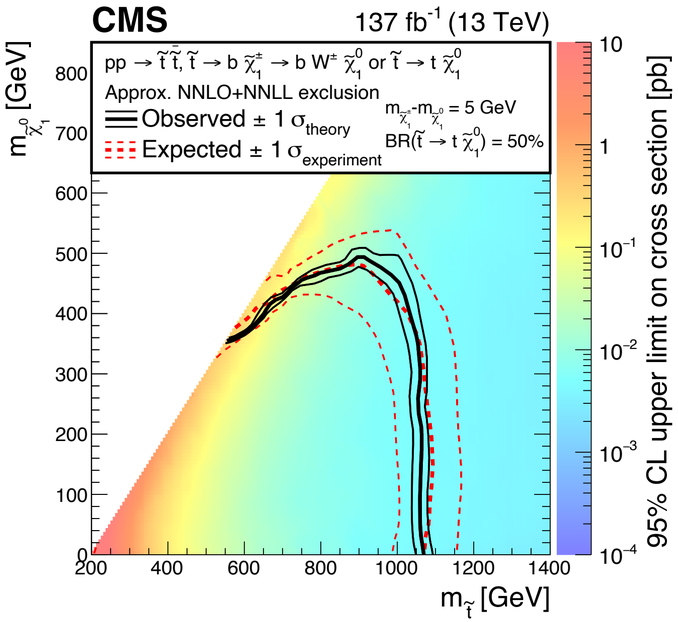
- Most important signal/background discriminator: $\not{E}_T$
- Most important background reduction method: $m_T > 150$ GeV



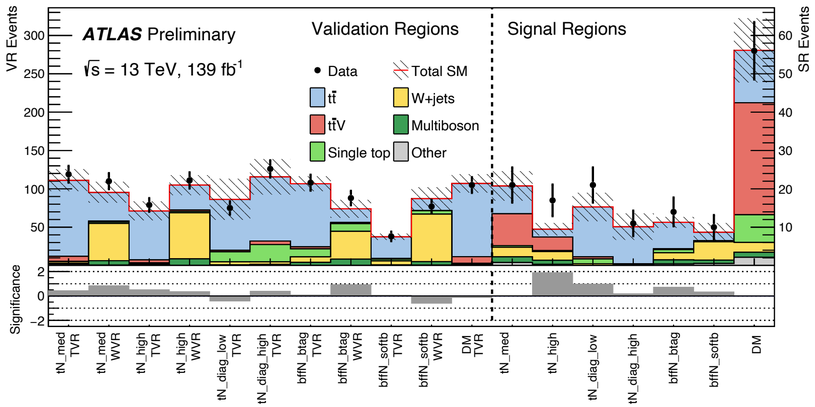


$$t_{\mathrm{mod}} = \ln(\min S), \text{ with } S = \frac{\left(m_W^2 - (p_\nu + p_\ell)^2\right)^2}{a_W^4} + \frac{\left(m_t^2 - (p_b + p_W)^2\right)^2}{a_t^4},$$





ATLAS Stop-1ℓ Search



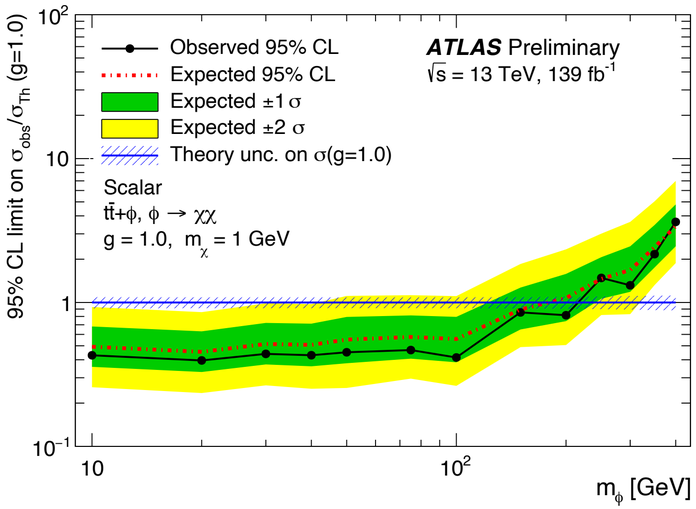


Table 7: Event selections defining the DM signal regions.

Selection		DM_scalar	DM_pseudo
Preselection		hard-lepton preselection	
N_{jet}, $N_{b\text{-jet}}$		$\geq (4, 2)$	
Jet p_{T}	[GeV]	$> (80, 60, 30, 25)$	
b-tagged jet p_{T}	[GeV]	$> (80, 25)$	
$E_{\text{T}}^{\text{miss}}$	[GeV]	> 230	
$H_{\text{T,sig}}^{\text{miss}}$		> 15	
m_{T}	[GeV]	> 180	
topness		> 8	
$m_{\text{top}}^{\text{reclustered}}$	[GeV]	> 150	
$\Delta\phi(\text{jet}_i, \vec{p}_{\text{T}}^{\text{miss}})$, $i \in [1, 4]$	[rad]	> 0.9	
$\Delta\phi(\vec{p}_{\text{T}}^{\text{miss}}, \ell)$	[rad]	> 1.1	> 1.5
Exclusion technique		Based on shape fit in $\Delta\phi(\vec{p}_{\text{T}}^{\text{miss}}, \ell)$	
Bin boundaries in $\Delta\phi(\vec{p}_{\text{T}}^{\text{miss}}, \ell)$		$\{1.1, 1.5, 2.0, 2.5, \pi\}$